

LH₂-fueled Cogeneration Unit with Fuel Cells

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1. DESCRIPTION OF THE PROJECT

Two major German utilities based in Hamburg, Hamburgische Electricitäts-Werke AG, HEW (electricity and district heating), and Hamburger Gaswerke GmbH, HGW (gas), have founded a joint venture (ARGE) to build and operate two phosphoric-acid fuel cells (PAFC) in urban surroundings. The PC25 fuel cells were purchased from the ONSI Corporation.

The first model used during the initial commercialization of fuel cells was called PC25A. This series was built between 1992 and 1997. The follow-up model "B" was used for military purposes only, and hardly changed compared to the A-model. The C-model has been improved in many ways, and it is smaller and easier to access. The cell stack has fewer cells but the total configuration has hardly been altered.

One fuel cell in this project was fueled by natural gas and the other by hydrogen. The performance of each cell was 200 kW_{el} and 220 kW_{therm}. In combination with an existing heat pump system, the fuel cells provided electricity and low-temperature district heating to residential buildings located at Lyserstrasse in Hamburg Bahrenfeld.

In a first stage (June 1995) the standard natural gas fuel cell was installed and put into operation. Subsequently, a hydrogen-fed fuel cell demonstration project was funded by as part of the EU's EQHHPP (Euro-Québec Hydro-Hydrogen Pilot Project) and was erected in 1997. The objectives of EQHHPP were to demonstrate a hydrogen fueled energy system in urban surroundings. The focus was not only on the technical and operational aspects of the first directly hydrogen-fueled PAFC to meet public utility demands, but also on questions of public acceptance and legal aspects of transporting and storing hydrogen within a densely populated European city.

The hydrogen infrastructure needed for the second stage consisted of a storage tank and refueling applications for liquid hydrogen (LH₂) and an evaporator for the fuel preparation. A road tanker delivered the hydrogen.

Although liquid hydrogen is stored in various industrial applications, this project is unique because it involves erecting the facility in a residential area. The challenges of the project with respect to the hydrogen storage tank were acceptance by the public and the relevant approval procedure.

2. LICENSE APPLICATION PROCESS WITHIN THE PROJECT

There were two main components subject to approval: the storage tank and the fuel cell unit.

2.1 The liquid hydrogen storage tank

This has been an important case in approving a hydrogen storage facility in an urban area and has required the acceptance of the residents. Therefore the ARGE HEW/HGW applied for

permission under the Federal Law on Ambient Air (Bundes-Immissionsschutzgesetz, BImSchG) through a full process with public participation, although a simplified procedure would have been sufficient. The pilot effect of this procedure was an important and intended result of the project. While the simplified procedure could have been completed in less than 6 months, this procedure took over a year.

Within the approval procedure there were four major activities. The first consisted of describing the planned work including all details such as drawings, materials, and operational procedures. Secondly, the Federal Institute for Materials Research and Testing (Bundesanstalt für Materialforschung und -prüfung, BAM, Berlin) carried out a safety opinion for the preliminary testing of a tank and evaporator plant for liquefied hydrogen. This was followed by an official announcement by the environmental authority during which the approval documents were open to the public and objections could be raised. Finally, a public hearing took place, and independent experts from the German safety authority TÜV answered remaining questions.

2.2 Approval for the hydrogen fuel cell

The fuel cell system is operated under the surveillance of the local safety authority (Amt für Arbeitsschutz, AfA). The first fuel cell was erected under the steam boiler federal regulation and was therefore subject to regular repeated safety checks. After becoming more familiar with the technology, the local authority decided that the fuel cell should be operated under the less costly and less demanding pressure vessel code, because all the produced steam is used for internal chemical processes (steam reforming). Therefore the second power plant received its operating permission under the federal regulation for pressure vessels (Druckbehälterverordnung). Only the primary cooling cycle operates under pressure (10 bar, saturated steam at 180°C) and is therefore the only sub-system of the fuel cell that needs to be approved by the local authorities.

The installation of the fuel cell in the second stage of the project provided the first electricity and district heating production in residential areas using hydrogen technologies. Since there was no regulation setting the approval procedure for the fuel cell CHP-unit and since the unit was not built according to European codes and standards (no CE-mark), the permit to run the power plant was granted for the pilot plant and with the stipulation that a safety check be made and that the power plant is only operated by specially trained service personnel.

The safety check determined that the biggest safety hazard of the entire fuel cell unit was the pressure vessel containing water and steam at an operating pressure of approx. 10 bars. Therefore the fuel cell unit had to be analyzed according to the pressure vessel code. Following the survey by the Hamburg labor inspectorate authority, the operation approval was granted.

3. OPERATION EXPERIENCE

During the operation phase of the hydrogen-fed fuel cell (starting 1st July, 1997 and ending on 2nd May, 2000) thorough tests were conducted to analyze the fuel cell and its operation in a district heating system.

3.1 Testing

By the end of April 2000 all of the planned tests were conducted and analyzed; allowing a concluding statement of the entire pilot project. The actual electrical efficiency at rated power dropped during the total time of operation from 42% to ~38%.

3.1.1 Power Test

Power tests were conducted during the operational period. The results can be seen in Diagram 1. Even though data from the beginning of the testing period is not included in the diagram, it shows how the efficiency at rated power decreased by approximately 3% between February 1998 and April 2000. In the very early phase of the project an efficiency of higher than 40% at full load was recorded resulting in an overall efficiency reduction of 5%. This process happened faster in the beginning of the operation and slowed down towards the end of the testing.

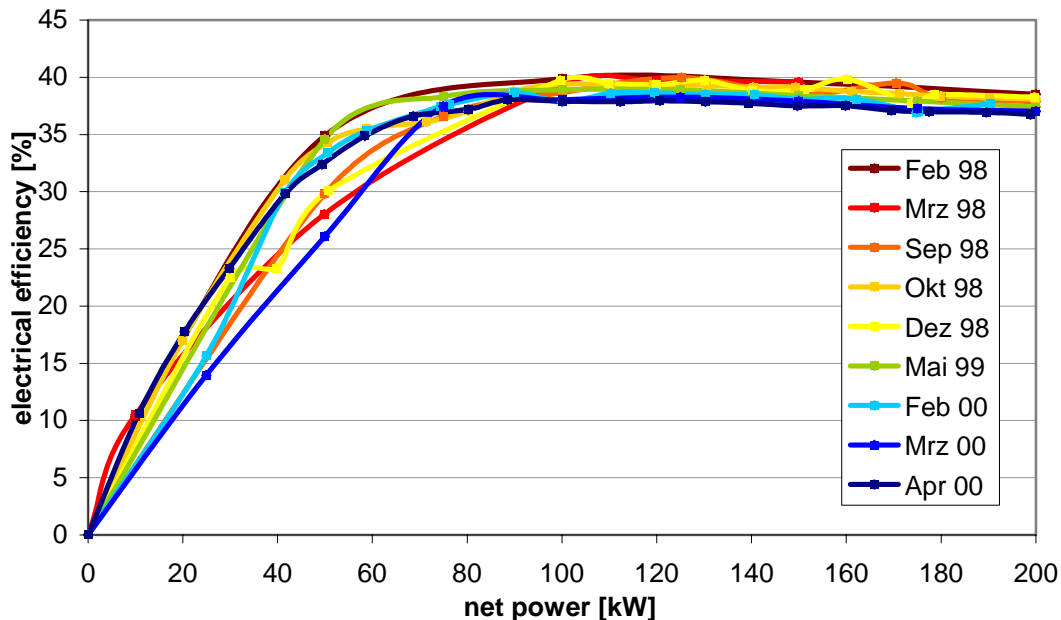


Diagram 1: Electrical efficiency decrease during the testing period.

Efficiency calculation at power levels below 50% load cannot be considered to be as precise because of a strong variation in internal energy consumption which has a great influence on the electrical efficiency.

3.1.2 Degradation

The reason for the drop in efficiency is degradation—typical for a phosphoric acid fuel cell. The reason for the degradation is both the reduction of the catalyst surface, which is platinum, and the loss of phosphoric acid from the electrolyte. In the test program, the effects of different operation situations on the speed of degradation is of major interest.

3.1.3 Heat driven mode

The main emphasis was put on operating in the heat driven mode. To analyze the power plant while running in the heat driven mode, various test cycles were run to compare the fuel cell with conventional CHP-units.

The ONSI-unit did not support a heat driven mode. It was, however, possible to relate the electrical and thermal output and to then follow the heat load diagram with the electrical set point value. This relationship can be seen for a single day in intermediate season in Diagram 2.

A load diagram was set up for a single day, starting at midnight. It resembled the load demand of a connected heating grid and described a specific heat demand for every moment. To simplify the diagram somewhat, the average set-point value was a five minute interval.

Three of the displayed heat load diagrams were taken from a conventional CHP-unit in Hamburg and represented loads from a winter, summer, and intermediate day. One load diagram was based on the German guideline (VDI-Richtlinie 2067) and represented a load for an average heating station on a winter day. By running the power plant according to these different loads, it is easy for any potential operator to compare their heat demand with the performance of this fuel cell unit.

With the combined use of electricity and heat, the overall efficiency was as high as 80% in the best cases. Considerable fluctuations were due to the fact that the thermal efficiency is strongly dependant on the temperature on the demand side, which was not very stable. However a higher temperature on the customer-heat-exchanger within the fuel cell would have helped to always deliver the required heat to the customer. German regulations require an overall efficiency of more than 70% for a unit operated under the CHP-law.

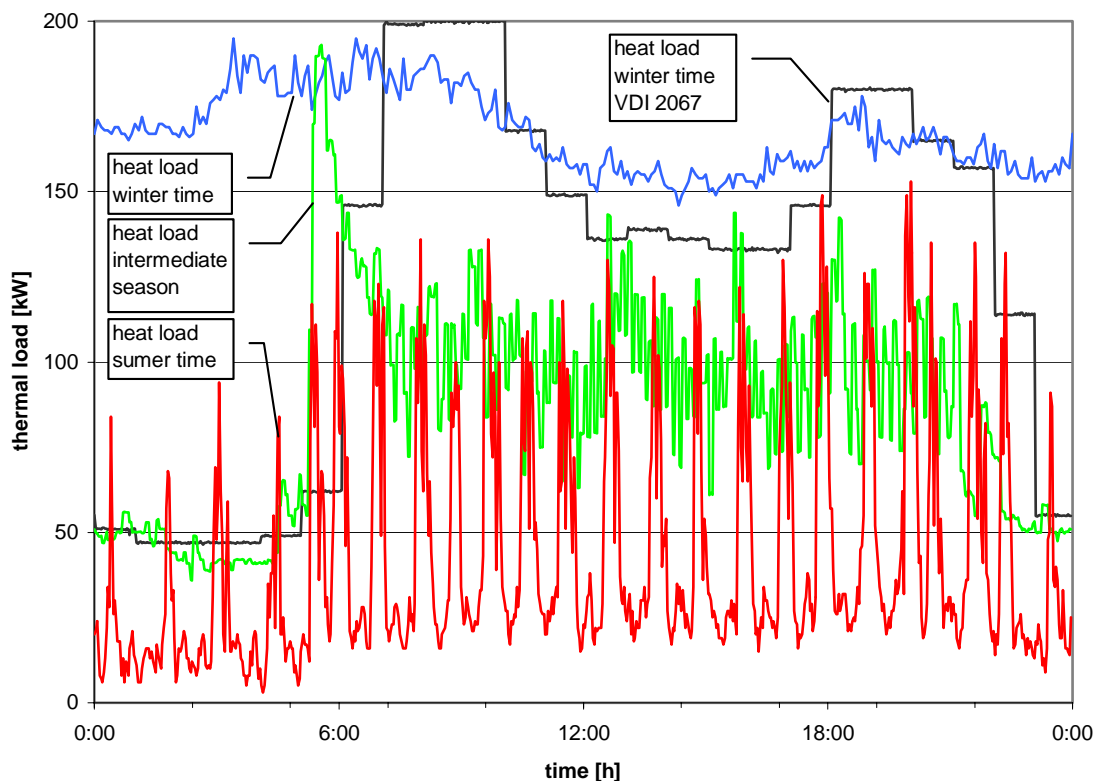


Diagram 2: Four different scenarios for a daily heat load: Three taken from a comparable conventional CHP-unit, one according to theoretical VDI data

The first most obvious result is that the fuel cell is able to adjust to any given load demand. The electrical out-put adapts to the new demand according to a load changing ramp controlled by the power plant controller.

However, the test results show that it took roughly 15 to 20 minutes for the fuel cell to adapt its temperature onto a new power level when the load was changed quite frequently. This indicates that the cell stack is not operating under optimal conditions.

Also, the low night time load level should be avoided when operating a phosphoric acid fuel cell. The temperature of the cell stack stays below its set point value even though electrical heaters are adding heat to the primary cooling loop. When running at approximately 20% of the rated power output, the fuel cell does not run efficiently—consuming too much hydrogen. A stable operation cannot be assured.

The result from the heat driven mode has been that the PC 25C-Hydrogen is not able to follow frequent rapid load changes without aging significantly faster. On the other hand, if needed, the power plant could adapt to a different load demand quickly and then benefit from its high efficiency at a broad load range.

3.2 Field experiences

Because this power plant was a prototype and therefore was not as reliable as a mass-produced CHP-unit, the failure analysis is somewhat less important. On the other hand, it indicated very clearly where the power plant did not achieve a standard sufficient for reliable operation and where the manufacturer has to improve the power plant.

3.2.1 Shut down analysis

A very positive experience from the field test has been that the cell stack—the major new development—has not once been the cause of failure. It proved to be reliable and can still be operated for a longer period of time.

The liquid hydrogen storage tank has demonstrated that it is possible to safely handle hydrogen. The technology to handle the hydrogen proved to be reliable and not once during the entire project was the storage tank subject to unscheduled maintenance.

On the other hand, this prototype fuel cell unit has shown a tendency towards failures in the primary cooling loop and the fuel processing system.

Table 1: List of major failures and duration of shut down time

| Reason for automatic shut down | Location |
|-----------------------------------|--|
| Heat exchanger leakage | Thermal management |
| Inverter failure | Power conditioning |
| Failure hydrogen recycling | Fuel process system |
| Broken coil on fuel valve | Fuel process system |
| High hydrogen consumption | Fuel process system |
| Low temperature / low voltage | Fuel process system / Thermal management |
| Failure on pressure sensor | Fuel process system |
| Air valve failure | Air process system |
| Power plant controller break down | Power plant controller |

A list of failures is shown in Table 1. These failures were responsible for 39 shut downs and an accumulated time out of operation of more than 550 days.

The development of the availability and the periods between failures can be seen in Diagram 3. In particular, long periods out of operation were caused by failures of the fuel processing system and the thermal management system. During the almost three-year operational phase, an operation time of 100% was achieved in only two months.

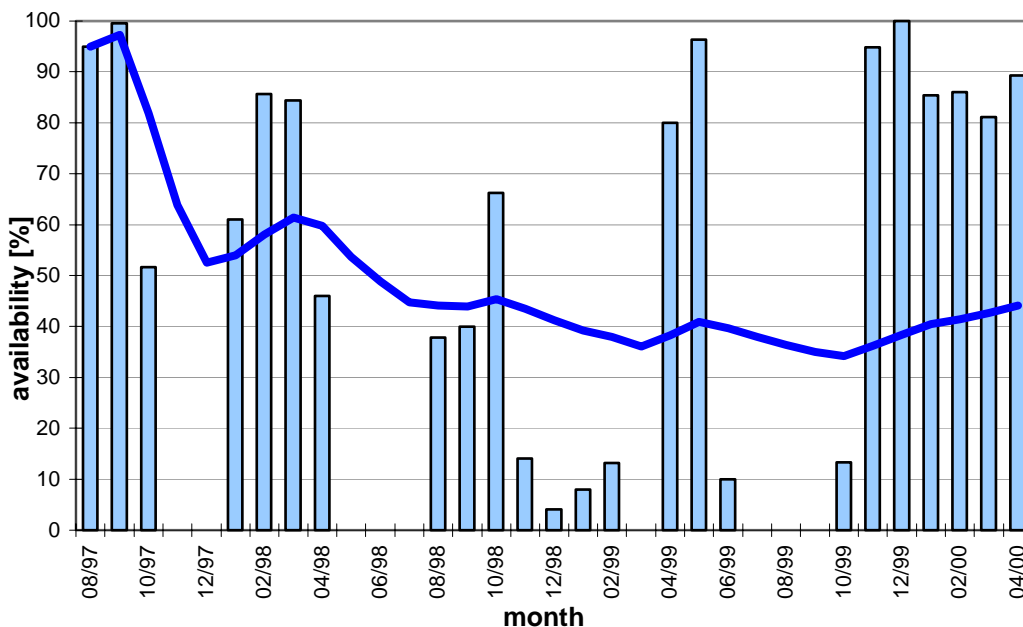


Diagram 3: Availability of fuel cell, monthly and accumulated

3.2.2 Maintenance

For the operator, the ability to conduct regular maintenance and occasional repairs is of major importance—especially since a prototype often has a slightly lower reliability. Compared to the earlier PC25A model power plant, the accessibility did significantly improve. This helped to bring the maintenance costs down, but delay was caused by the long time it took to deliver necessary spare parts from the manufacturer to the site.

Regular maintenance involving exchange of demineralization bottles, filters, and pumps causes no problem. However, spare parts are very costly and prevent a real commercial operation.

4. ACCEPTANCE

The erection of the hydrogen storage tank and the fuel cell and the operation of both have been very well accepted by the neighbors. After the public hearing no further complaints have been raised officially.

However, at the beginning of the hydrogen fuel cell's operation period the noise emissions were far too high for operation in an urban area. The external cooler and all the ventilation fans in the fuel cell cabinet were a major source of noise emissions. Within days, silencers at all fans and at the air in- and outlets were added.

The project has achieved a lot of public attention. Frequent visitors from schools, universities, gas and electrical utilities, and chemical industries from all over the world visited the site. They were very interested in the feasibility of both fuel cell and hydrogen technology. Questions raised on these occasions were aimed towards

- when will fuel cell technology be sufficiently developed to be market competitive?
- where will hydrogen be implemented first into the energy market?

The first question can be easily answered by the operational experience. It is connected to the status of the further fuel cell development—mostly focusing on technical reliability and reduction of investment cost. The project demonstrated very well the near-to-market-entry of the technology by operating according to commercial practice.

The question of hydrogen as an energy carrier has repeatedly given rise to discussions about energy efficiency and sustainable development. It was, however, recognized that the handling of hydrogen does not imply a greater risk but rather that hydrogen was been successfully presented as a clean energy carrier. It certainly proved to be very important that the handling of hydrogen and the storage tank has been reliable.

5. CONCLUSIONS

5.1 Fuel cell operation in Hamburg

The PC25C power plant in its configuration demonstrated in Hamburg showed an early phase of a CHP-development for fuel cells. In certain operations like partial load it clearly demonstrated its advantages over conventional reciprocating engines. However at this developmental stage the fuel cell could not maintain good results over a long period of time due to insufficient set-up of the controls.

The environmental advantage was demonstrated according to expectations. The exhaust measurements have shown that the level of emissions was far below any comparable conventional CHP-unit and some emissions, like sulfur-components, were not even measurable. This, in combination with its good electrical efficiency, will help to market fuel cells in the future.

Due to the pilot nature of the project, the investment costs were too high and the reliability was too low for operation on a commercial basis. Further development is needed to bring the investment costs down and to raise the availability. Main emphasis for the further development should be:

- reducing the degradation of the stack,
- improving the balance of the plant for better performance,
- increasing the reliability of the balance of plant,
- cost reduction.

The electrical efficiency of between 50% and 100% rated output (100 kW and 200 kW) was better than any comparably sized technology. However, at lower power levels the efficiency decreases so that operation under these conditions is not advisable. A system in which the fuel cell is operated best should allow a large number of operation hours between full load and 50% load without too many load changes. This could be a system that allows the power plant to run on full load during daytime and partial load at night. Excess heat should be stored in a hot water

tank, which then can supply additional heat during peak demand. Compared to a conventional CHP-unit this could possibly avoid the use of a gas burner for peak load.

5.2 Commercialization potential

Fuel cells in general are of great interest for the electricity market. They provide a tool to generate electricity and heat on-site or near the customer without the need for housing or chimney. Fuel cells can easily be monitored from remote locations so that a utility can supply its customers with heat and power service.

However, to be cost effective—especially in the deregulated market today—the investment cost has to be comparable to conventional CHP-units. Providing that fuel cells will be cheaper in the future, they will be a very good alternative wherever the supply from the public grid is more expensive or the emission regulations are strict.

Due to the modular composition of fuel cells, they can be imagined in various applications from household to large CHP-units. They can be operated singularly or in connection to other fuel cells and therefore can provide a back-up to each other in addition to conventional CHP-units; supplying these with means to control the load.

Centralized large fuel cell power plants will probably not be competitive because of the very low investment cost of big conventional thermal power plants.

However, as the electricity market shifts towards a more decentralized structure due to stable energy consumption and lower risk from smaller investments, fuel cells will most likely be one of the available and appropriate technologies. Small residential fuel cells in the 5-10 kW range will be able to supply heat and electricity in urban areas and larger fuel cells will supply industries or office buildings where the heat and power demand fits the relevant fuel cells heat-to-power-ratio and a large number of full load operating hours can be guaranteed.

6. CONTACT INFORMATION

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|--------------------------|---|
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7. ANNEX: PICTURES



Drawing 1: Fuel cell CHP-site Lyserstrasse Hamburg Bahrenfeld

| | |
|--------------|----------------------------------|
| EGBZ | natural gas fuel cell |
| H2BZ | hydrogen fuel cell |
| KÜ | cooling module |
| LW | control room |
| VERD | evaporator |
| H2TL | hydrogen storage tank |
| HGS | hot water, natural gas, nitrogen |
| Heizzentrale | heating station |



Picture 2: Hydrogen storage tank seen from the side, fuel cell and the supplied buildings in the background



Picture 3: Hydrogen fuel cell in the front and natural gas fuel cell in the middle (with sign)



Picture 4: Hydrogen fuel cell and storage tank



Picture 5: Top view of the site